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Clues on the nature of low-z radio sources from the 2dFGRS

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Abstract. We use redshift determinations and spectral analysis of galaxies in the 2dF Galaxy Redshift Survey to study the properties of local radio sources with $S \geq 1$ mJy.

1. The Datasets

The 2dF Galaxy Redshift Survey (2dFGRS[1]; Maddox, 1998) is a large-scale survey aimed at obtaining spectra for 250,000 galaxies to an extinction-corrected limit for completeness of $b_J = 19.45$ over an area of 2151 square degrees. Redshifts for all the sources brighter than $b_J = 19.45$ are determined in two independent ways, via both cross-correlation of the spectra with specified absorption-line templates and by emission-line fitting. The success rate in redshift acquisition is estimated about 95 per cent. The median redshift of the galaxies is 0.11 and the great majority have $z < 0.3$.

Radio observations come from the FIRST (Faint Images of the Radio Sky at Twenty centimetres) survey (Becker et al. 1995), estimated to be 95 per cent complete at 2 mJy and 80 per cent complete at 1 mJy. Optical counterparts for a sub-sample of FIRST sources have then been obtained by matching together objects included in the radio catalogue with objects coming from the APM survey in the overlapping region $9^h48^m \lesssim \mathrm{RA(2000)} \lesssim 14^h32^m$ and $-2.77^\circ \lesssim \mathrm{dec(2000)} \lesssim 2.25^\circ$. Out of approximately 24,000 radio sources with $S \geq 1$ mJy in the considered area, Magliocchetti & Maddox (2001) find 4075 identifications in the APM catalogue for $b_J \leq 22$ (the limiting magnitude of the APM survey) and 971 for $b_J \leq 19.45$ (the completeness limit of the 2dFGRS), both obtained for a matching radius of 2 arcsecs. 2dF data then provided optical spectra for 557 objects with $b_J \leq 19.45$ and $S \geq 1$ mJy, corresponding to 53 per cent of the original sample. This apparent incompleteness is merely due to incomplete sky coverage of the spectroscopic survey. Neither radio nor magnitude biases have been found in the determination of the optical and spectroscopic counterparts of FIRST radio sources.

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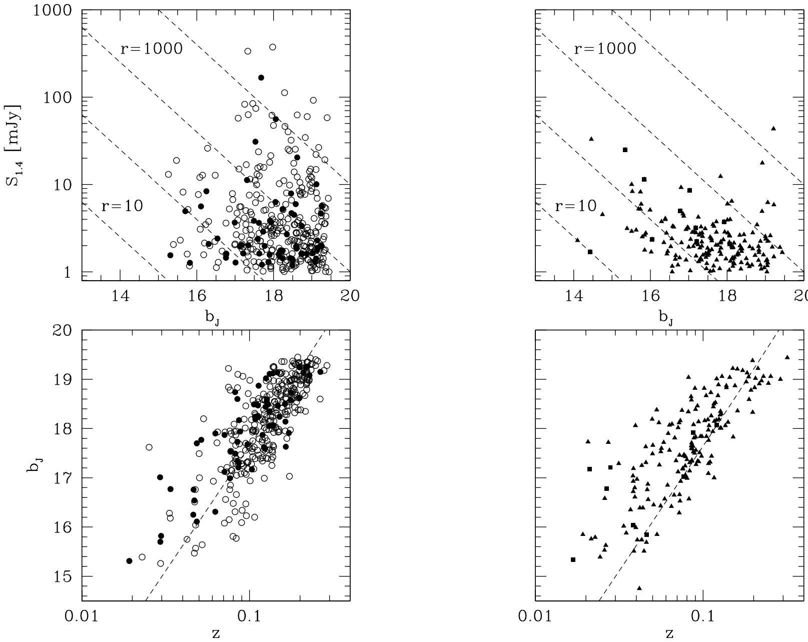

Figure 1. b_J magnitudes versus radio flux S at 1.4 GHz (top panels) and redshift (bottom panels). Plots are derived for early-type (empty circles) and E+AGN (filled circles) galaxies, late-type (filled triangles) galaxies and starbursts (filled squares). The dashed lines in the top panels correspond to constant values of the radio-to-optical ratios $r = 1 - 10^4$, while those in the $b_J - z$ plots represent the best fit to the data obtained for the population of early-type galaxies (see text for details).

2. Properties of the Sample

Classes for the optical counterparts of radio sources have been assigned on the basis of their 2dF spectra which allowed galaxies to be divided into 4 broad categories. As Fig.1 shows, different classes occupy different regions on the $S - b_J$ and b_J-z planes, reflecting the different intrinsic characteristics of the populations which we summarize here:

1) **Early-type galaxies** show spectra dominated by continuum which is much stronger than the intensity of any emission line. This class comprises 289 objects and makes up 52 per cent of the whole spectroscopic sample. Sources belonging to this population tend to have relatively high values for the radio-to-optical ratio, $r = S \times 10^{(b_j - 12.5)/2.5}$ ($100 \lesssim r \lesssim 10^4$) and are preferentially found for redshifts $z \gtrsim 0.1$. The majority of these sources show rather red colours ($b_J - R \gtrsim 1$), with a tendency to be redder at larger look-back times. Their radio fluxes lie in the range $1 \lesssim S/\mathrm{mJy} \lesssim 10$, even though objects are found up to $S \sim 400$ mJy, and optically they appear as relatively faint (about 60 per cent of the sources has $b_J \geq 18$). The $b_J - z$ relation in this case (represented by the dashed line in the bottom-left panel of Fig. 1) is well described by the expression $b_J - M_B = -5 + 5\,\log_{10} d_L(\mathrm{pc})$, ($d_L$ is the luminosity distance), with $M_B \simeq -21.3$ for an $h_0 = 0.5$, $\Omega_0 = 1$ universe, showing that passive radio galaxies are reliable standard candles.

2) **E+AGN-type galaxies** show spectra typical of early-types plus the presence of (narrow) emission lines which indicate the presence of an active nucleus. There are 61 objects in this class, corresponding to 11 per cent of the spectroscopic sample. These sources are directly connected to the class of early-type galaxies, even though they show characteristics that are intermediate between pure AGN-fuelled sources and star-forming galaxies. Optically they appear as rather faint and closely follow the standard-candle relationship found for early-type galaxies. However their radio-to-optical ratios are in general as low as those obtained for late-type galaxies. Their radio fluxes are in general quite low and their $b_J - R$ colours are uniformly distributed between about 0 and 2.
3)-4) **Late-type galaxies** and **Starbursts** have spectra which show strong emission lines characteristic of star-formation activity, either together with a detectable (late-type) or missing (starbursts) continuum. This class comprises 177 objects (including 10 starbursts), which is ~ 30 per cent of the spectroscopic sample. The radio-to-optical ratios r for these sources have values in general smaller than those found for early-type galaxies. Their radio fluxes are rarely brighter than $S \simeq 5$ mJy and optically they have bright apparent magnitudes (very few objects are found with $b_J \gtrsim 18.5$). These sources have quite blue colours, $-2 \lesssim b_J - R \lesssim 1$, and are mostly local – the majority of them being located within $z \simeq 0.1$. Furthermore, they show a weaker correlation between b_J magnitudes and redshift than found for the previous classes of objects, and do not follow the $b_J - z$ relation found for early-type galaxies (illustrated by the dashed line in the bottom panels of Fig. 1).
Note that we also found 18 Seyfert 2 and 4 Seyfert 1 galaxies. For further discussion and the whole list of objects see Magliocchetti et al. (2001).

Some information on the above classes of sources can also be derived from the few optical images showing resolved structures. For instance, it is interesting to note that the majority of the interacting/merging systems seems to be associated with early-type spectra, typical of pure AGN-fuelled sources, suggesting that merging, under appropriate conditions, can trigger AGN activity even at low redshifts. Also, as expected, irregulars and spirals preferentially show spectra typical of late-type galaxies; signatures of interaction and/or merging are seen for members of this latter population as well as for E+AGN galaxies. Finally, radio images show that there is a clear trend for extended/sub-structured sources to be associated with absorption systems (i.e. early-type galaxies).

Radio powers have subsequently been calculated according to the relation $P_{1.4\rm GHz} = S_{1.4\rm GHz} D^2 (1+z)^{3+\alpha}$, with D angular diameter distance and α spectral index of the radio emission, and the local radio LF for objects in the spectroscopic sample has been derived by grouping the sources in bins of width $\Delta \log_{10} P = 0.4$, according to the expression $\Phi(P) = \sum_i N_i(P, P+\Delta P)/V^i_{\rm max}(P)$ where N_i is the number of objects with luminosities between P and $P+\Delta P$ and $V^i_{\rm max}(P)$ is the maximum comoving volume within which an object could have been detected above the radio-flux and magnitude limit of the survey. We set $S = 1$ mJy for the radio-flux limit, while $b_J = 19.45$ is the chosen magnitude limit and the results for the local LF have been corrected for incompleteness effects coming from both the radio and the spectroscopic surveys.
This was done for each population taken individually. Fig.2 shows the results for the early-type (lower panel), early plus E+AGN (middle panel) and late-type+starburst (top panel) galaxies. The dashed line in the bottom and middle

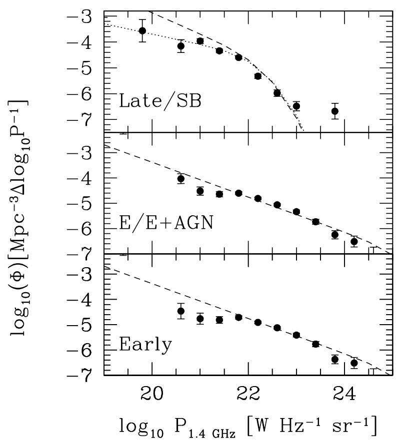

Figure 2. Local radio luminosity function at 1.4 GHz for late-type+starburst galaxies (top panel), early and E+AGN galaxies (middle panel) and early-type galaxies only (bottom panel).

panels of the Figure is the predicted LF for steep spectrum FR I+FR II sources as given by Dunlop & Peacock (1990) under the assumption of pure luminosity evolution. In this case the agreement with the data is very good down to powers $P \simeq 10^{20.5}\,\mathrm{W\,Hz^{-1}sr^{-1}}$, especially if one includes all the objects which show spectra typical of early-type galaxies, regardless the presence of emission lines of AGN origin. The LF for late-type galaxies and starbursts is shown in the top panel of Fig.2, and features a break at about $P \simeq 10^{22}\,\mathrm{W\,Hz^{-1}sr^{-1}}$, beyond which the contribution of this class of objects becomes rapidly negligible. When it comes to a comparison between observed and predicted LF for this latter case, one has that a good description of the data is provided by the Rowan-Robinson et al. (1993) model (dashed line in the top panel of Fig.2), which can correctly reproduce both the broken power-law behaviour and the break luminosity, therefore supporting the assumption of these authors for late-type radio galaxies to be identified with the population of dusty spirals and starbursts observed at 60 μm. However, the Rowan-Robinson et al. (1993) predictions result in an over-estimate of the number of faint (i.e. $P \lesssim 10^{21}\,\mathrm{W\,Hz^{-1}sr^{-1}}$) radio sources, while the best fit is provided by assuming a shallower faint-end slope for the local LF, as illustrated by the dotted line in Fig.2 (see Magliocchetti et al. 2001 for more details).

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